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Increasing the functional properties of helical springs by using of SiCr-alloyed oil hardened spring steel wire with optimized strength and forming behavior

SESSION 7 - ENGINEERING DESIGN

The paper presents a few of the experimental results obtained in investigations aimed at improving the properties of spring steel wire made of SiCr alloys and oil-hardened affecting their processing and operating properties for manufacturing high quality helical springs [1]. These results were obtained by systematic analysis of the wire tempering process, systematic control of variables and selection of materials of a standard to fit the purpose .

INITIAL SITUATION

As specifications become ever more sophisticated, there is a need to improve the precision of helical compression springs: this involves evaluating and optimizing the entire production process of the raw material (spring steel wire), with regard to strength and forming behavior. In the case of oil-hardened and tempered spring steel wire, improving the adjustment of the different quenching and tempering process parameters will help meet the need: a systematic investigation and the results achieved are described here, as are the properties of helical compression springs produced with various types of hardened and tempered spring steel wire.
There is a central problem: spring manufactures demand good forming behavior with the yield stress kept as low as possible, while springs in their function and use demand strength as high as possible, together with a high capacity for energy storage [2][3]. The limits on strengths are set by the cold-shaping during spring manufacture, as high-strength spring steel wire is of limited ductility. This applies particularly to oil-hardened spring steel wire alloyed with silicon and chromium, specially designed for springs to be exposed to high dynamic and thermal demands.

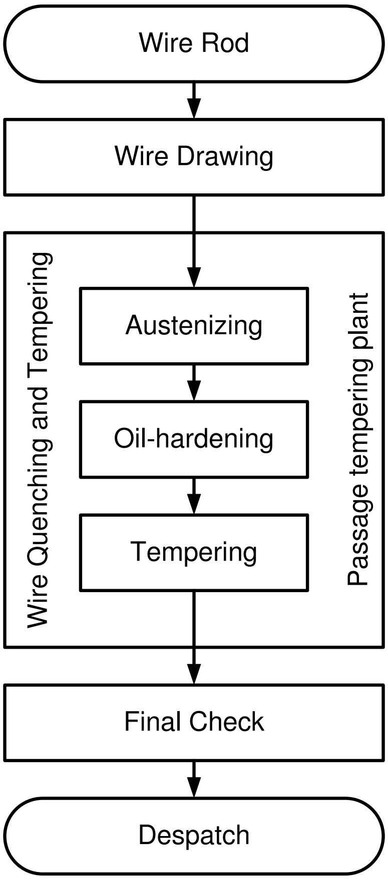

Figure 1: Simplified process, production of oil-hardened spring steel wire

There are reserves within the hardening process (Figure 1) that can be used to improve the process and use characteristics of oil-hardened spring steel wire. The temperature and period of the austenising, the composition of the quenching fluid, the temperature of the lead bath used in tempering the hardened wire, and the passage velocity selected will all have a crucial influence on the crystal structure change and thus on the strength and forming behaviour of the wire. It should be noted in addition that current wire manufacture regards the tensile strength R_m as the most important parameter, so that all optimisation procedures tend to be directed at improvement of R_m. However, torsion is the chief demand placed upon compression springs in use. To set the dimensions of these springs, the technical yield point under torsional stress $\tau_{t0.04}$ is required, a value which is at present calculated on the basis of a constant relationship with the tensile strength R_m:

$$\tau_{t0.04} = 0.56 \cdot R_m \text{ as per DIN 13906 [4]} \quad (1)$$

This constant relationship, independent of the material, is, however, a fiction, because the material qualities on which it is based (for instance, homogenous and isotropic) simply do not apply to spring steel wire on account of the way it is manufactured. The constant can therefore only be used as an approximation.
One significant reason for the approximation is that no testing station has so far

existed to enable torsion parameters to be calculated for spring wire, whereas tensile testing has long been established.

To meet future challenges facing compression springs, there is a urgent necessity to improve the torsion characteristics of spring steel wire, at the same time finding a means of recording them as measurements.

In the “Festigkeits- und Umformverhalten” Research Project (Tensile and Forming Behaviour) [1] [5], vital basic information was obtained and this has been put to practical use already as far as possible in the context of the project. It has been of immense use to both wire and spring manufacturers.

AIMS AND PROCEDURE

The main purpose of the research was to establish the influence exercised by the process parameters on the properties of spring steel wire during quenching and tempering (Figure 2), and to apply the knowledge obtained so as to produce sample wires with their strength and shaping properties optimised for the manufacture of springs with improved function. It was a major focus to raise the technical yield point under torsional stress $\tau_{t0.04}$. The higher this limit, the better the potential exploitation of the material. Raising the limit makes it possible to produce springs for a specific task of lower mass than previously known.

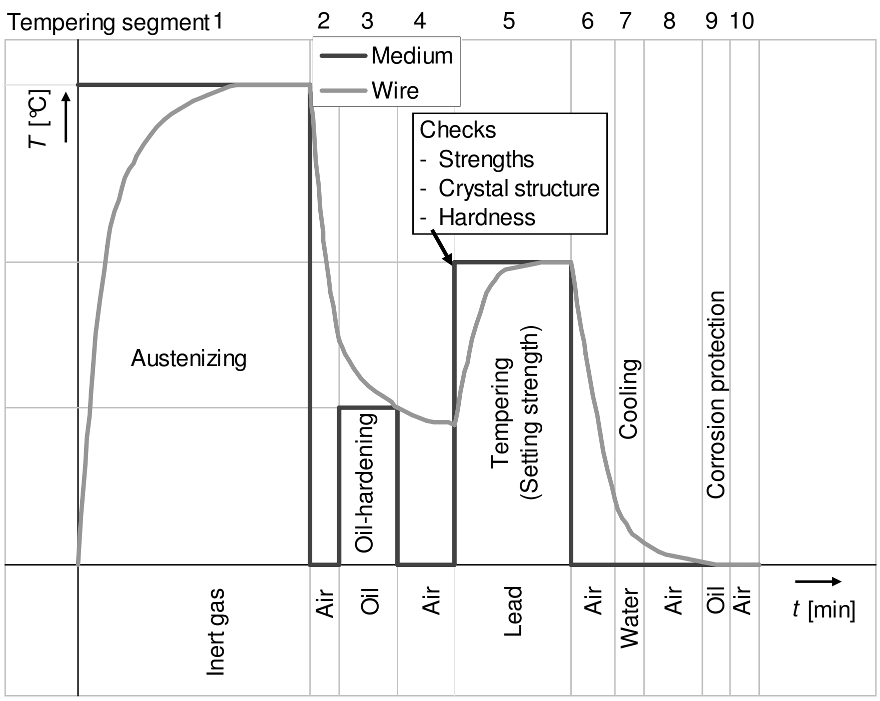

Figure 2: Stages of the tempering process

Two research items required for the project aims to be achieved were:

- Selection of tempering regime to improve the strength of the wires while ensuring that parameters do not drop below given minima for the shaping characteristics (elongation before reduction of area A_g, reduction in cross-section at breaking point Z, number of twists N_t).
- Production of compression springs made of spring wire which has undergone a variety of passage tempering to permit the spring properties to be evaluated in relation to the wire properties obtained from the different processing methods.

Nominal values for the variously-treated samples of wire were determined in tensile, torsion and rotation bar bending fatigue tests. The values established for the springs were those of the behaviour as to pre-set process parameters and relaxation.

Four levels of material quality used in the production of oil-hardened spring wire were used for two sizes of diameter, and some of these were peeled wire (Table 1).

Table 1: Types of wire used in main experiments

Material	Dimensions
54SiCr6 SC	Wire rod d = 8.00 mm ➔ drawn wire d = 4.50 mm
	Wire rod d = 5.50 mm ➔ peeled d = 5.05 mm ➔ drawn wire d = 1.90 mm
65SiCrV6	Wire rod d = 8.00 mm ➔ drawn wire d = 4.50 mm
	Wire rod d = 8.00 mm ➔ peeled d = 5.05 mm ➔ drawn wire d = 1.90 mm
75SiCrV6	Wire rod d = 8.00 mm ➔ drawn wire d = 4.50 mm
	Wire rod d = 5.50 mm ➔ peeled d = 5.05 mm ➔ drawn wire d = 1.90 mm
52SiCrNi5	Wire rod d = 5.50 mm ➔ peeled d = 5.05 mm ➔ drawn wire d = 1.90 mm

Knowledge gained

Considerable quantities of new data have been obtained. Only some significant are mentioned in the remainder of this paper.

HOW THE PASSAGE TEMPERING PARAMETERS AFFECT THE STRENGTH AND FORMING BEHAVIOUR OF THE SPRING STEEL WIRE

Within the project, fundamental knowledge was obtained with the aim of establishing the process parameters from the passage quenching and tempering which might be adjusted in order to influence the torsional properties of the spring steel wire.

Experiments were therefore carried out to establish the influence of the four important process parameters (austenising temperature and period, tempering temperature and period) on the torsional properties of the wire. This means that practical suggestions can be made for the setting of process parameters according to which aspect of the wire requires optimisation. Indeed, the user must in future be able to state the purpose for which the wire, i.e. the spring, is to be employed, so that the wire manufacturer can apply the most suitable passage tempering conditions.

NOMINAL WIRE VALUES OF RELEVANCE TO SPRINGS

There is no fixed relationship of 0.56 between the nominal values (e.g. R_m) obtained in tensile tests and those obtained in torsional tests (e.g. $\tau_{t0.04}$) which are relevant to helical springs (Figure 3). It is therefore necessary that the question of which values require optimisation in view of the later use of the wire will be clarified at the stage when the tempering parameters are set.

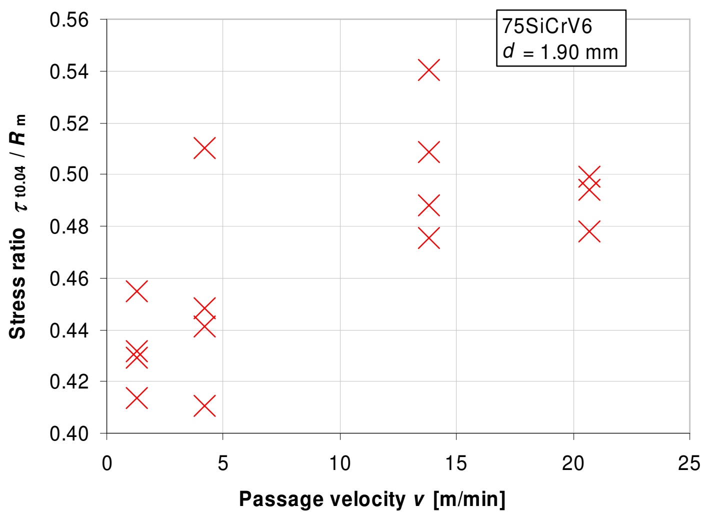

Figure 3: Alterations to the $\tau_{t0.04}$ / R_m ratio due to the tempering parameters
Every data point is the result of one quenching and tempering regime.

Spring manufacturers should note that it is important in future for calculations and manufacture in the case of helical springs not to take the tension nominal values of the spring steel wire, but to take the torsional values. It will be necessary to set up suitable testing equipment in this connection [6].

Currently the improvement of wire is largely aimed at increasing the tensile strength R_m. However, it has now been shown that the technical yield point under torsional stress $\tau_{t0.04}$, which is highly significant for the functioning and design of helical springs, will react to changes in tempering parameters differently then other properties as the tensile strength R_m.

A field test was undertaken, investigating how the process parameters of the quenching and tempering process affect the wire parameters. Therefore the austenising temperature (parameter A), the austenising period (parameter B), the tempering temperature (parameter E) and the tempering period (parameter F) were varied in a wide range.

As is shown in Figure 4, it is easy to influence the tensile strength R_m by altering the tempering parameters. On the other hand, the significance of the austenising temperature and period is much higher for the technical yield point under torsional stress $\tau_{t0.04}$ (Figure 5). Thus it is clear that the raising of the tensile strength R_m currently sought by targeted regulation of the tempering parameters is not bound to lead to an improvement in the torsional properties of the wire.

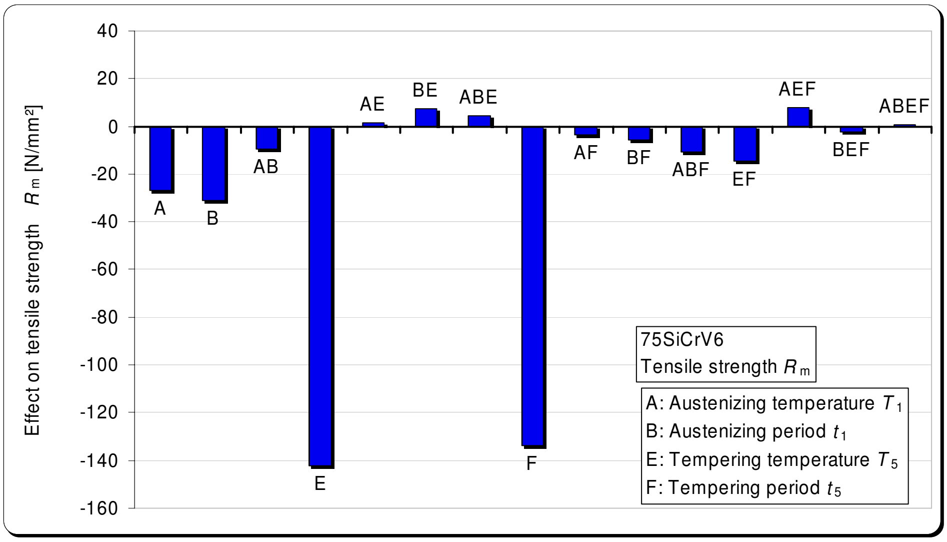

Figure 4: Altering tensile strength R_m by means of tempering parameters

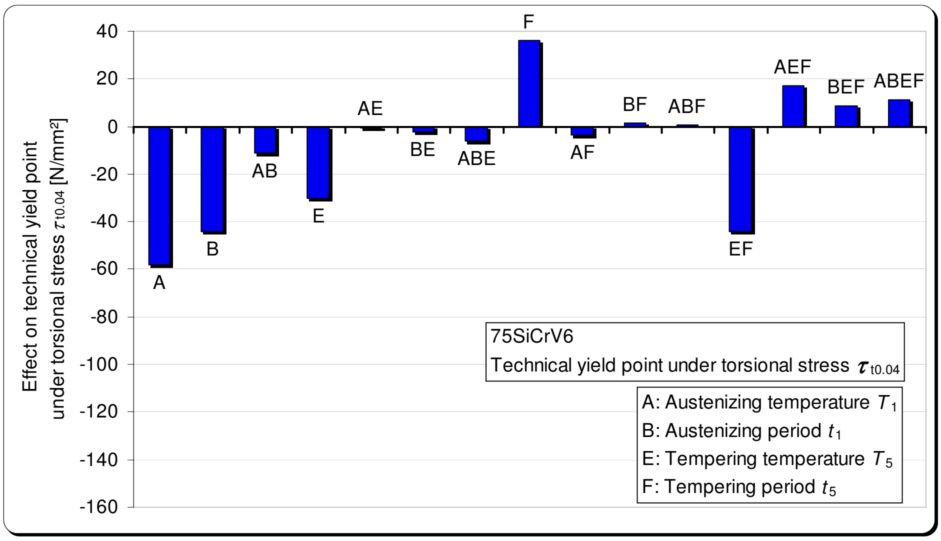

Figure 5: Altering technical yield point under torsional stress $\tau t0.04$ by means of tempering parameters

Note on Figure 4 and Figure 5:
If negative values are shown for the tempering parameters this means that reducing them raises the nominal value for the wire. The longer the bar the greater the effect of the tempering parameter. Positive values are to be understood analogously.

PROPERTIES OF HELICAL SPRINGS MADE OF VARIOUSLY TEMPERED WIRE

A number of series of springs were manufactured for the purposes of investigating helical spring properties when these are made from materials that have been differently tempered. One parameter taken especially into account was the length of the spring. This was manufactured with two values by varying the pitch while the other nominal values were kept identical (Table 2). One of the variables established was the alteration in spring length at the pre-setting stage of the spring manufacturing process. The experimental results permit statements as to how the tempering regime used in the wire manufacture affects the pre-setting behaviour of the springs.

Table 2: Parameters of springs investigated

Spring parameter	Unit	Springs with normal pitch	Springs with larger pitch
Wire diameter d	[mm]	1.9	1.9
Mean spring diameter D	[mm]	14.71	14.71
Number of active coils n_f		4.5	4.5
Free length of compression spring L_0 before setting	[mm]	**36.9**	**42.4**

All springs were manufactured using the same process parameters for spring tempering, shot peening and pre-setting.
Not only the static nominal values also the dynamic properties of the springs made of variously tempered wire were established. A large number of fatigue tests was carried out for the purpose, using, for example, the servo-hydraulic test machinery of the “Research Group Springs” (Forschungsgruppe Federn) at the Technische Universität Ilmenau. The parameters in Table 3 were investigated for all the series of springs.

Table 3: Parameters subjected to fatigue tests for springs of free length L_0 = 42.4 mm

Stress values	Unit	Level 1	Level 2
Maximum stress τko	[N/mm²]	1250	1100
Minimum stress τku	[N/mm²]	100	100
Difference between maximum and minimum stress τkh	[N/mm²]	1150	1000
Testing frequency f	[Hz]	15	15

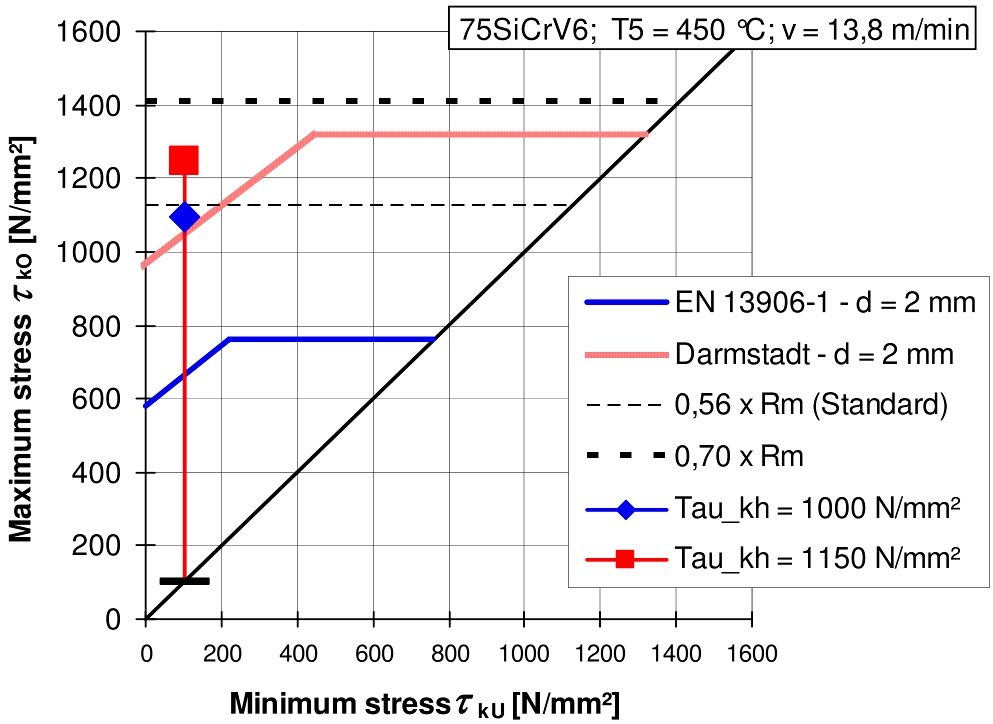

Figure 6: Stress levels investigated for springs with larger pitch (with a high τ / R_m ratio)

The stress levels shown in the form of a Goodman graphic, Figure 6, reveal that the maximum stress investigated, τ_{ko}, is above those for standard springs with $N = 10^7$ as the number of alternations. The highest possible stress levels for the experiments were selected, in order to provoke spring failure and enable a choice of the best wire to provide springs with the best dynamic properties.

For helical compression springs made with passage tempered wire of d = 1.9 mm, the following important experimental results were obtained (see also Figure 7):

- Higher strength, which is influenced particularly by tempering after coiling (a source of increased strength), will reduce the pre-setting losses for the springs.
- As far as relaxation behaviour is concerned the wires with the greatest strength demonstrate, as might be expected, the lowest losses through relaxation.

– Over a difference τ_{kh} = 1000 N/mm² between maximum and minimum stress levels, springs made of the 54SiCr6 SC Super-Clean wire demonstrate on average a higher number of stress cycles than springs not made of this type of wire.
– The number of stress cycles achieved is not clearly related to the strength of the wire. Springs made from wire with some nickel content are an exception to this rule, in that their quality is much poorer. Another exception is springs made from the two types of 75SiCrV6 wire and possessing high strength. These have double the average lifetime.

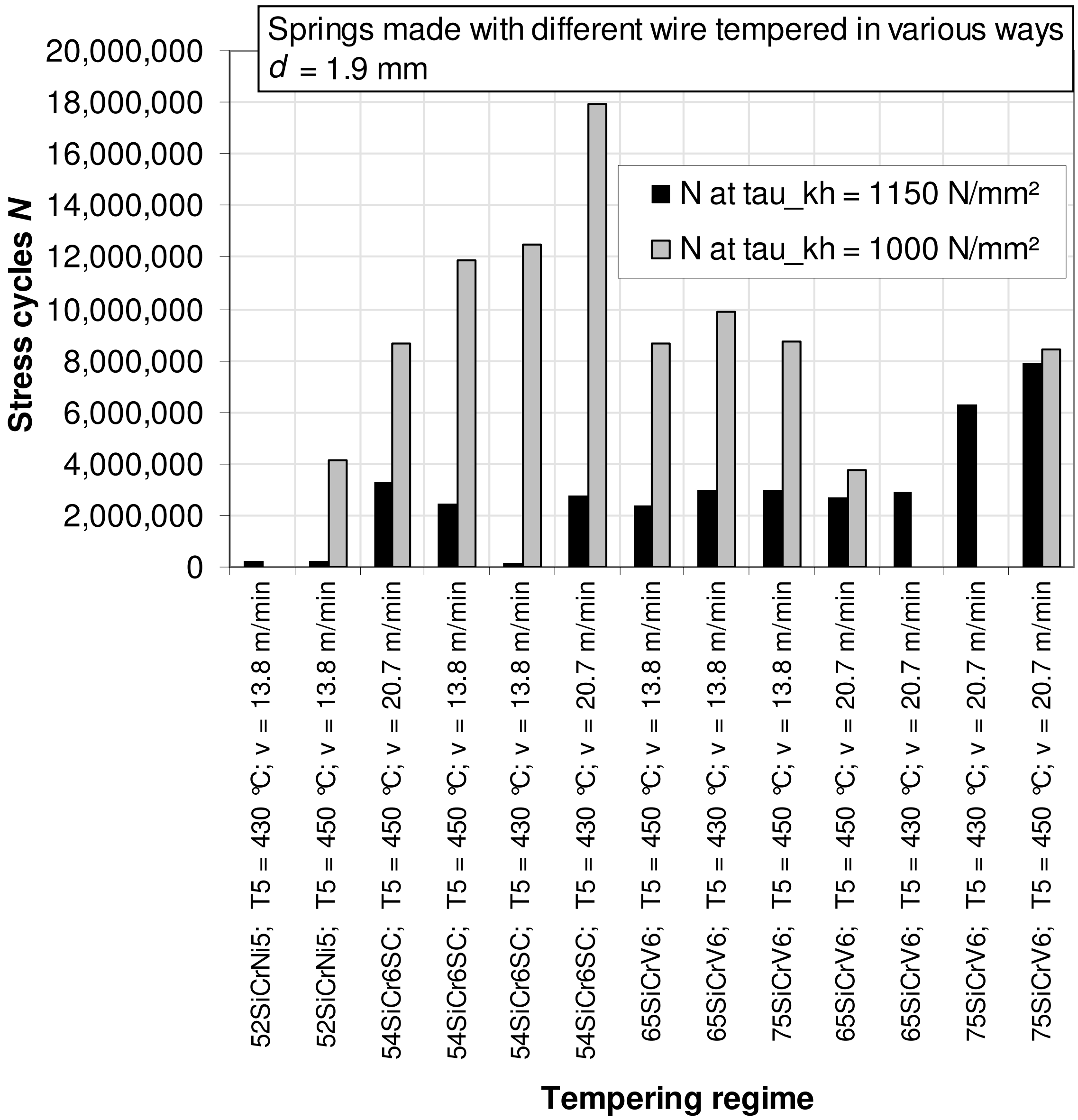

Figure 7: Comparison of number of stress cycles achieved in relation to type of tempering

CONCLUSIONS AND OUTLOOK

This paper has presented a few of the experimental results obtained in investigations aimed at improving the properties of spring steel wire made of SiCr alloys and oil-hardened: properties affecting both use and ease of processing. These results were obtained by systematic analysis of the wire tempering process, systematic control of variables and selection of materials of a standard to fit the purpose.

The experimental outcomes raised the limits of tempering process parameters well above those customary at present. It will be possible in future to select tempering parameters which increase productivity on account of higher passage velocity in the tempering plant, also saving energy costs on account of lower austenising temperatures.

However, the experiments have also proved that it will only be possible to achieve further improvement of spring wire properties if a total view is taken in future of the manufacture of spring wire and springs. Research is being planned on this subject. When all the experimental results are considered (not all of them have been presented here), it is clear that an even more thorough investigation of the manufacturing process for spring steel wire is needed. It will be necessary to take into account not only the spring wire production (and the desire to optimise the tempering process and other parameters) but also the spring production and post-treatment (including tempering and shot peening after the coiling process) when aiming at the improvement of the wire [7][8].

The tempering process must be controlled in such a way that the wire leaves the wire manufacturer with bending-and-forming properties that are suitable for the coiling of springs even with a low spring index, and that it possesses the highest possible torsional strength $\tau_{t0.04}$ even after proceeding through all the further manufacturing stages and ending up as a spring.

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Besides the authors, the following members of staff at the Faculty of Mechanical Engineering of the Technische Universität Ilmenau have been involved in the research: Dr. Veronika Geinitz, Peter Beyer, Ina Bretschneider and Jürgen Remdt.

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